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Waste-to-Taste: Transforming Wet Byproducts of the Food Industry into New Nutritious Foods

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Abstract: Food and beverage production generates enormous amounts of spent residues in the form of pomaces, pulps, grains, skins, seeds, *etc.* Although these sidestreams remain nutritious, their conversion to foods can be complicated by issues of digestibility and processing, particularly when the residues are wet and therefore highly susceptible to microbial degradation. Ideally, these sidestreams could be stabilized and then re-circulated into food, instead of being diverted to waste, animal feed, or biofuels. Indeed, the end-of-life of our food crops is increasingly important to consider in the context of circularity, ensuring that land, water, and chemical inputs to agriculture are sustainable. In the context of wet byproducts from the food industry, we discuss two separate case studies that look at how to valorize and extend the longevity of nutritionally-rich but underutilized sidestreams. The first study examines the fermentation of okara into an edible tempeh-like cake, while the second investigates ProSeed's approach to drying and valorizing brewer's spent grain. We conclude with some words on the nuance and challenges involved in saving from waste the highly perishable but nutritious side products of current food and beverage production.

Keywords: Brewer's spent grain · Drying · Fermentation · Food ingredients · Food waste · Okara

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Pictured from left to right: Aurélien Ducrey, Anna Koptelova, Tiffany Abitbol, Natalia Nagornova, Bénédicte Lunven, and Edouard Appenzeller. Not pictured: Léa Köller.

1. Introduction

The impact of our food and agricultural systems on the planetary boundaries first proposed by Rockström *et al.* in 2009 is undeniable.[1] Indeed, humanity has currently transgressed 6 out of 9 planetary boundaries, with our agricultural and food systems strongly implicated in these negative impacts.[2] As just a few examples, it is estimated that these systems contribute roughly 11% of all anthropogenic CO_2 emissions, that cropland and pastures occupy 40% of land surface (where Rockström *et al.*[1] recommended no more than 15%), that nitrogen fertilizer use has increased by >800% from 1960–2000, with only about 50% of that nitrogen actually becoming integrated into plant biomass, and that this unrestrained use of nitrogen has further contributed to atmospheric N_2O, a potent ozone depleting substance.[3] At the same time, humanity's agricultural output had to increase in order to feed the Earth's growing population, projected to reach 9.7 billion by 2050.[4] Indeed, the Haber-Bosch process, a chemical process that enabled the fixation of nitrogen from the atmosphere, where it is the most abundant molecule, into ammonia that could be used as fertilizer is often credited for enabling the food production needed for the population to grow in the first place.[5]

Undeniably, many places in the world are still enjoying a time of plenty and prosperity that could only be dreamed of in previous generations. However, this has led to a depletion of natural capital that oftentimes outpaces population growth, to the extent that we currently overshoot our ecological resources at alarming speed, using up the capacity of about 1.7 earths per year.[6] What is also clear is that our resources are not divided equally among the inhabitants of the planet. For instance, considering agricultural output, while many of us enjoy an overabundance and access to many more calories than are actually good for us, others are starving. Furthermore, a strange paradox has emerged, referred to as the triple burden of malnutrition, wherein undernutrition, overnutrition, and micronutrient deficiencies can all co-exist within the same population,[7] reflecting that despite an overload of calories contributing to growing obesity rates, many are still 'starving' due

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to lack of key nutrients and a growing proportion of empty calories in our food. How is this to be reconciled? On the one hand, we produce, consume, and waste too much, and on the other hand, many of us do not have access to key nutrition, and are effectively starving.

It is within this context that we consider food waste, and in particular, wet byproducts of the food and beverage industry. These streams can be overlooked and undervalued as they are secondary to main product lines and may not have a straightforward business path for producers. The challenges around many of these wet byproducts are that, even though they still possess nutritional value, they are highly perishable, and industrial-scale strategies to stabilize and extend shelf-life can be prohibitively expensive and difficult to justify for use cases that are niche, low volume, low value, or are not yet well-elaborated. In this article, we describe two case studies that provide possible scenarios that could be used to extend the value and lifetime of these wet-byproducts beyond their current end-of-life, which in Switzerland is mainly relegated to animal feed and biogas.[8] We ask ourselves how we can transform these byproducts into valuable foods in their own rights and describe several challenges we encountered along this path to valorization. Indeed, there is no one size fits all approach, and eventually whether or not these byproducts will be destined for new food products, will depend on many factors, including nutritional value, digestibility, taste, and cost. In the first case study, we look at the fermentation of okara, a byproduct of soy milk and tofu production, to create a tempeh-like food, using the starting okara in as near as possible to its as-produced form, keeping it wet throughout our processing. In the second case, we share the story of ProSeed, a Swiss startup, that integrates on-site drying units to extend the shelf-life of sidestreams, facilitating the transformation of the wet byproduct of one industry (*e.g.* spent grain from brewing) into an ingredient or product for another industry (*e.g.* barley flakes as a standalone ingredient).

2. Case Study 1: Okara Tempeh

The 2024 UNEP Food Waste Index Report indicates that over 1 billion tonnes of food were discarded in 2022, accounting for one-fifth of all food available to consumers.[9] Additionally, 13% is lost in the supply chain before it even reaches store shelves, primarily due to the waste of byproducts.[9] One example of such waste is okara.[10]

Okara is a byproduct generated during the production of soy milk and tofu.[11] The production of soy milk begins with soaking dried soybeans in water, followed by grinding them into a fine slurry, which is then boiled for 10-20 minutes.[12] Next, the milky slurry is filtered to separate the soy milk from the solid residue, which is commonly referred to as okara. Okara consists of the insoluble parts of the soybeans, including fiber and protein.[10] With 1 kg of processed soybeans yielding 1.2 kg of fresh okara, its global production is substantial, amounting to around 14 million tonnes annually.[13]

Dried okara contains 42.4–58.1% dietary fiber (lignocellulose), 15.2–33.4% protein, and 8.3-10.9% lipids,[9] along with components such as isoflavones, which makes it a potentially valuable resource for both human and animal consumption.[10] Due to its nutritional composition, large scale of production, and low cost as a byproduct, okara is often considered a valuable ingredient for animal feed.[11,13] For example, it can serve as a protein source for young pigs, contributing up to 25% of their overall nutritional intake.[13] Okara can also be used as a fertilizer because of its high content of dietary fiber, which can enhance soil structure and promote microbial activity, overall supporting soil fertility and plant growth.[11]

Fresh okara is consumed in China and Japan, providing a simple way to enrich diets in fiber and protein,[14] however its consumption is not common in other parts of the world, where it can be considered unpalatable due to a grassy or beany taste. Okara is of interest as a functional food ingredient due to its nutritional profile, phytochemicals, and potential prebiotic effects.[14] For instance, its ability to bind moisture and oil, can make it interesting as a value-added ingredient in processed meats and baked goods, improving nutrition, without altering flavor or texture.[14,15] However, for these types of uses, the okara is usually first dried, which can be challenging to implement and costly.

The practical use of fresh okara is thus limited by its high moisture content, which can range from 70–80%, or even higher. This significantly reduces its shelf life and complicates storage and transportation.[10] The high moisture content promotes the growth of microorganisms, resulting in off odors and the potential for microbial contamination of surrounding sites.[16] In the absence of immediate processing or preservation, okara spoils within days, even if it is refrigerated, representing an enormous bottleneck to its valorization.[13,17] Extending the shelf life of okara, while maintaining its nutritional value, usually requires that it be stabilized in some way, such as by freezing or drying. Drying lowers the moisture content, thereby inhibiting microbial activity and extending shelf-life.[18]

Another promising approach to extend the lifespan of fresh okara is through solid state fungal fermentation, which can reduce or eliminate the need for drying.[19] Solid state fermentation transforms the composition of okara and can enhance its functional properties.[19] Tempeh, a traditional Indonesian food, is based on the fermentation of boiled and dehulled soybeans with different strains of *Rhizopus spp*, such as *Rhizopus oligosporus* (*R. oligosporus*).[20] The fungal mycelium binds the beans together and improves digestibility.[20] The resulting product - tempeh - can be sliced, diced, and cooked similarly to tofu, and analogous foods have been produced with okara in the place of the soybeans.

Fermentation can improve the nutritional profile of beans by reducing anti-nutritional factors and increasing the availability of essential nutrients and improving digestibility.[20] For instance, the fermentation of chickpeas with *R. oligosporus* to produce a tempeh flour significantly reduced insoluble dietary fibers and phytic acid, while increasing levels of soluble dietary fibers and free amino acids.[20] Considering okara, Vong *et al*.[21] observed significant improvements in the nutritional profile of okara tempeh fermented with *R. oligosporus* and *Yarrowia lipolytican*.[21] Their findings included a 33% reduction in insoluble dietary fibers, a 16% reduction in phytic acid, a 176% increase in soluble dietary fibers, and a 254% increase in free amino acids.[21]

This case study described here further explores the potential of converting fresh okara into tempeh-like cakes through solid state fermentation, with a focus on optimizing fermentation parameters and the wet content of the starting okara. Perhaps, most importantly, we found that some drying was required prior to fermentation, since fermentation of the as-produced okara with a water content >80 wt% did not support healthy or timely mycelium development, leading to spoilage (as judged by off odors) before the formation of a cohesive cake could be obtained. Okara particles are smaller than soybeans, leading to a more densely packed substrate, which can make it challenging to ensure sufficient air circulation needed for successful fermentation, especially at higher moisture contents.

2.1 *Okara Fermentation*

2.1.1 *Materials*

Frozen okara (provided fresh by Migros Industrie and frozen within hours of its production to preserve for further use), *R. oligosporus* starter culture (purchased online from Madame Ferment; http://madameferment.com), *Pleurotus ostreatus* (*P. ostreatus*) mother culture grown on agar plates (purchased from Mycelia, Belgium). Vinegar and rice flour were purchased from the local Migros grocery store. Commercial soybean tempeh, tempeh natur, produced by tempehmanufaktur (Germany; https://www.tempehshop.de/) was purchased from a local grocery.

2.1.2 *Materials Characterization*

Polarized optical microscopy (Nikon Eclipse LV100N POL, red waveplate) was used to visualize the different samples. Sample preparation involved flattening a thin sliver of sample between a glass slide and a coverslip. This type of microscopy highlights birefringent materials, such as cellulosic fibers, which appear turquoise or yellow (color difference is a 90° in plane rotation) against a bright pink background. ATR-FTIR analysis (Perkin-Elmer Spectrum 3 spectrometer) was used to identify the major chemical components in the samples based on their characteristic absorptions. The wavenumber range of 4000–650 cm^{-1} was probed, with each spectrum an average of 8 scans obtained at a resolution of 4 cm^{-1}. Nutritional analysis (Eurofins Laboratories) was conducted to quantify nutritional profile, including carbohydrate, protein, fat, lipid, and moisture contents. We recalculated these results on a dry weight basis to facilitate the comparison of different foods with different water contents.

2.1.3 *Solid State Fermentation*

Thawed okara was first mixed with vinegar to lower the pH and prevent bacterial contamination. Next, okara and all necessary utensils were autoclaved at 121 °C for 45 minutes to sterilize. After sterilization, the okara was blended in a kitchen mixer (Kenwood Chef XL mod. KVL60) for 2 minutes. The okara was inoculated with the fungi and mixed for another 2 minutes. The mixture was then placed into autoclavable bags that were pierced with holes to allow air circulation and filled to a thickness no greater than 2–3 cm. The bags were kept in an incubator at 26 °C and 80% relative humidity or in an Instant Pot® Duo™ (a pressure cooker with a yogurt mode) at around 30 °C with distilled water added to the bottom of the pot to provide humidity. The pot was left vented to allow sufficient air circulation for successful fermentation. Finally, once the okara tempeh had reached the desired texture, which was cohesive and cake-like, it was vacuum-sealed and stored in the freezer.

2.1.4 *Fungal Species*

Two fungal species were initially explored, *R. oligosporus*, a traditional tempeh starter known for forming a dense mycelium layer that effectively binds soybeans, and *P. ostreatus*, another common and edible species. In our hands, fermentation with *P. ostreatus* yielded a less dense mycelium layer and produced an off-putting odor. Therefore, we opted to focus on *R. oligosporus* in our subsequent trials. Still, eventually, it might be interesting to study fermentation with other fungal species, even revisiting *P. ostreatus*. Indeed, to use *P. ostreatus*, we harvested pure mycelium from the surfaces of an inoculated agar plate and then mixed it together with rice flour to achieve something similar to the commercial *R. oligosporus* starter, but our approach was not normalized in any way (*e.g.* by CFU).

2.1.5 *Influence of Incubation Temperature*

We compared two incubation temperatures: 26 °C and 30 °C. At 26 °C, fermentation was slow, producing a thinner mycelium surface skin with off odors suggesting suboptimal fungal growth and microbial contamination. In contrast, fermentation at 30 °C led to the formation of a thick, homogeneous mycelium skin and was therefore selected in subsequent experiments.

2.1.6 *Influence of Moisture Content*

Moisture content emerged as a critical factor in determining the quality of the fermented product. While maintaining a wet product 'as-is' is beneficial for minimizing energy and processing steps, some drying was required. The initial okara provided by Migros Industrie had a moisture content of 82.4 wt%. Fermentation at this moisture content led to inhomogeneous mycelium development, off odors, and an overall pasty mass, regardless of fermentation temperature (26 °C or 30 °C). As mentioned, a possible explanation is that air circulation was impeded in this wet and dense substrate, interfering with mycelium development. A few different lab-scale approaches were attempted to reduce the moisture content to levels that supported healthy mycelium growth, including fully drying in an oven (100 °C) and then rehydrating to the desired levels (50–70 wt%), partial dewatering by pressing/vacuum filtration in a Buchner funnel, and partial drying in an oven (100 °C). Based on these trials, partial oven drying to a 70 wt% moisture level was selected as most convenient and efficient, additionally resulting in a dense and uniform tempeh. Subsequent experiments used okara with a 70 wt% moisture content.

2.1.7 *Influence of Starter Amount*

The amount of commercial starter culture significantly influenced the consistency of the fermented product. The commercial supplier recommended 5 g/kg starter to produce a tempeh from soybeans, whereas we found that 15 g/kg was more appropriate considering the okara substrate. This is presumably due to the higher specific surface area and airflow requirements of okara compared to soybeans. Using 15 g/kg resulted in a thicker mycelium and improved binding of the okara particles. Subsequent experiments were performed at this level.

2.1.8 *Influence of Incubation Time*

The optimal incubation time was found to be 48 hours. Prolonged incubation (72 h) led to a spoiled product, whereas shorter incubation times (24 h) resulted in incomplete mycelium formation and compromised the cohesiveness of the cake.

2.2 *Okara Tempeh*

We focused our remaining efforts on the tempeh-like cakes produced from *R. oligosporus*, incubated at 30 °C for 48 hours, with a starter amount of 15 g/kg, and a 70 wt%, moisture content

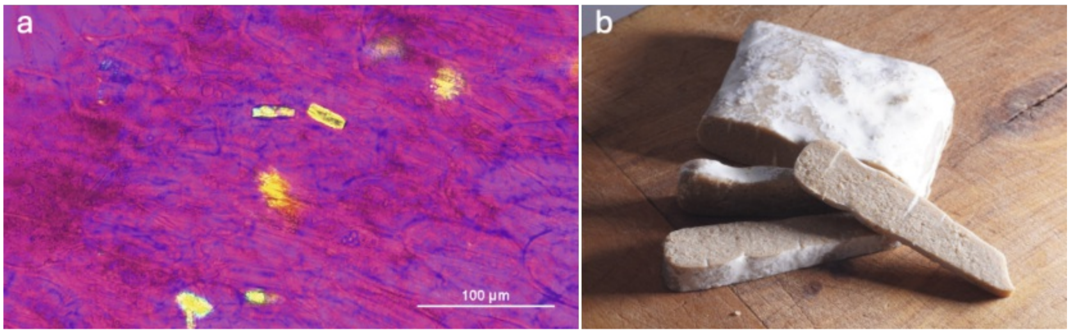

Fig. 1. Polarized optical microscope image of initial okara, showing birefringent elements and cell wall fragments (a) and photograph of okara tempeh produced as outlined above (b).

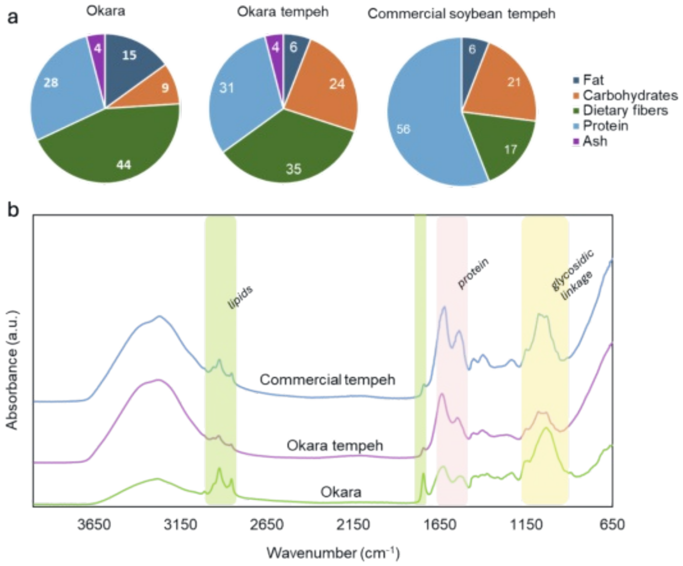

Fig. 2. Nutritional contents on dry mass basis in % for starting okara, okara tempeh (produced in this work using optimized conditions), and a commercial soybean tempeh (a). ATR-FTIR spectra of the same samples (b). Note that the nutritional values for the commercial tempeh were calculated from the product's nutritional label, and that the moisture contents of the ATR-FTIR samples differed: okara was oven dried, whereas the okara tempeh had a moisture content of 70% and the commercial tempeh 50%.

of the okara due to the superior characteristics of the resulting tempeh: cohesive cake, dense mycelium skin, no off odors. The initial thawed okara and the as-produced okara tempeh are shown in Fig. 1.

Fermentation initiates several biochemical transformations in okara, significantly altering its nutritional profile, with potential implications for digestibility (as demonstrated by others). In Fig. 2a, we show the nutritional values for the starting okara, our okara tempeh, and a commercial soybean tempeh.

The nutritional profile of a commercial soybean tempeh consists approximately of 56% protein, 21% carbohydrates, 17% dietary fiber, and 6% fat (Fig. 2a). In comparison, okara tempeh is nutritionally depleted in protein (31% *vs.* 56%) and enriched in dietary fiber (35% *vs.* 17%). This is consistent with the differences in the substrates, okara *vs.* soybeans, as okara is the insoluble fraction of the soybean, depleted in protein, which is transferred to soy milk and tofu, and enriched in insoluble/non-digestible dietary fibers (lignocellulose). Otherwise, both tempeh products have similar fat and carbohydrate contents.

Comparison of the okara tempeh to the starting okara shows a modest increase in protein content with fermentation, probably due to the growth of protein-containing mycelium. Also consistent with the growth of mycelium is the decrease in dietary fibers (35% *vs.* 44%) and the increase in carbohydrates (24% *vs.* 9%) due to the breakdown of dietary fibers into simpler, more digestible forms. The fat content was significantly reduced (6% *vs.* 15%) likely due to the digestion of lipids during fermentation.

ATR-FTIR analysis further confirmed the compositional differences between okara, okara tempeh, and commercial soybean tempeh (Fig. 2b). According to the literature,[20] the main absorptions corresponding to the different macronutrients are as follows:

- **Lipids**: 2700–3000 cm^{-1} and 1740 cm^{-1}
- **Polysaccharides**: 600–1400 cm^{-1}
- **Proteins**: 1650 cm^{-1} (amide I) and 1550 cm^{-1} (amide II)

Additionally, we highlight the absorption around 1035 cm^{-1}, which is indicative of the glycosidic linkage in cellulose. The ATR-FTIR spectra generally support the results of the nutritional analysis although they are less quantitative as the samples were analyzed at different moisture contents. As mentioned above, fermentation modifies fiber composition, converting a part of okara's insoluble dietary fibers into soluble fibers and carbohydrates, which can enhance digestibility and benefit the gut microbiota.[22] ATR-FTIR supports this conclusion as the glycosidic absorption decreases relative to the protein absorption in comparing the starting okara to the okara tempeh.

In this project we compositionally modified okara by solid state fermentation (Fig. 1). Parameters such as incubation time, incubation temperature, moisture content, and starter amount were investigated to produce an okara tempeh with qualities similar to traditional soybean tempeh, thereby transforming a food waste into a food to taste. Additionally, we aimed to extend the shelf life of okara and enhance its digestibility. Indeed, the fermented cakes withstood spoilage during the fermentation process, whereas okara is unable to withstand storage at 30 °C for 48 h. The balance between soluble and insoluble carbohydrates was changed in a way that could potentially improve digestibility.

The tempeh that we produced had a neutral aroma, becoming nutty with cooking, and a mealy texture, reflective of the particle size of the okara. Further work will be needed to optimize the texture of this food and make it more appealing for human consumption, for instance by pelletizing the okara prior to fermentation or mixing it with a proportion of beans, as is done by Luya, a Swiss company that produces a food product from the fermentation of okara and chickpeas.[23] Interestingly, despite the addition of chickpeas to the Luya product, the nutritional profile of the 'Simply Natural Luya Chunks all-natural and ready to go' product, as listed on their webpage,[23] is remarkably similar to the okara tempeh produced in this work.

Overall, our work supports the valorization of okara into a new food, while also attempting to address the elephant in the room when it comes to wet food byproducts, which is the challenge of using these sidestreams before they rot. We showed that the initial wet okara does not need to be completely dried (partial drying is sufficient) and that the changes in nutritional values elicited by fermentation can be beneficial. Ideally, implementation of these ideas at scale would extend the soymilk/tofu making process by directly coupling it to fermentation, without needing to dry, store, freeze, refrigerate, or otherwise stabilize the okara.

3. Case Study 2: ProSeed's Approach to Upcycling Brewer's Spent Grain

ProSeed is a Swiss startup that offers an innovative, on-site drying solution aimed at upcycling wet byproducts from food and beverage processors into valuable raw materials. The company integrates containerized drying units directly into production lines, allowing processors to convert their wet byproducts into shelf-stable, profit-generating materials, which can be reused in the food industry. In this study, we focus on ProSeed's work within the brewing industry, where brewer's spent grain (BSG) – a high-moisture byproduct of beer production – is transformed into a raw material called Barley Flakes. These flakes are ideal substrates for solid state fermentation and are used by ingredient manufacturers to produce high-fiber, high-protein ingredients for bakery products, pasta, and meat alternatives.

3.1 *Understanding Brewer's Spent Grain: Generation, Handling, and Composition*

BSG is the primary byproduct of the brewing industry, accounting for approximately 85% of the total byproducts generated during the brewing process.[24] For every hectoliter of beer produced, 14 to 20 kg of BSG are generated.[25] In Switzerland alone, more than 80,000 tonnes of BSG are produced annually by breweries.[26]

The main ingredient in beer, after water, is barley malt.[24] The barley malt is milled, mashed, and filtered, resulting in two fractions: wort (liquid) and BSG (solid). While the wort continues in the beer production process, BSG is treated as a byproduct (Fig. 3).

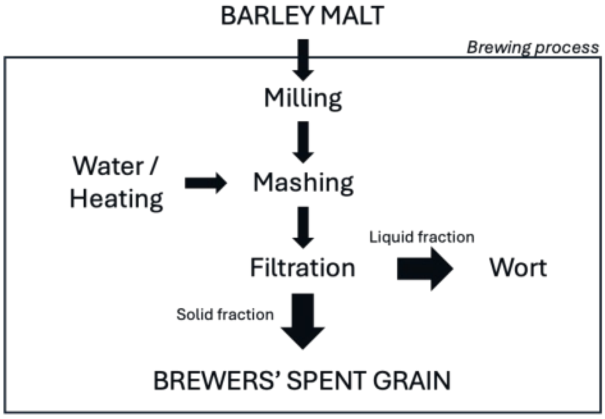

Fig. 3. Brewing process leading to Brewer's Spent Grain.

As produced, BSG has a high moisture content of approximately 80%,[27] and a temperature of around 65 °C,[28] making it highly perishable once it begins to cool. Without rapid processing or stabilization, BSG can spoil quickly, making it unsuitable for human consumption. Traditionally, BSG has been used in low-value applications such as animal feed and energy production.[29]

The composition of BSG varies according to the barley variety, harvest time, malting and mashing conditions, and the quality and type of adjuncts added during the brewing process.[30]

Generally, BSG is considered a lignocellulosic material, as it is mainly composed of the outer layers of the seed, rich in lignin, cellulose, hemicellulose, lipids, and proteins.[27] Since most of the barley starch is removed during malting and mashing, protein and fiber are concentrated in BSG, comprising around 20% protein and 70% fiber (dry basis),[24] making it highly attractive for human food applications.

3.2 *Challenges in Upcycling BSG*

One of the main challenges in upcycling BSG for human consumption is maintaining its food-grade quality. Like okara, due to its high moisture content, BSG is highly susceptible to spoilage shortly after it exits the brewing process.[31] This rapid degradation compromises its safety for food applications, necessitating prompt processing or stabilization to maintain its quality for further use.

Additionally, the wet form of BSG makes transportation costly,[8] as it involves moving large quantities of water. Existing food manufacturing supply chains are designed to process dry materials, making it difficult to integrate wet byproducts like BSG into the production process without significant adjustments. This combination of rapid spoilage risks, food safety concerns, and logistical constraints makes the upcycling of BSG into food-grade ingredients particularly challenging.

Today, BSG is primarily used for low-value applications such as animal feed and biogas production. However, these methods fail to capture the full nutritional potential of BSG. Valorizing BSG in a cost-effective, energy-efficient, and scalable manner, while maintaining food-grade quality, remains challenging. Previous efforts have faced obstacles related to food safety, logistics, and scalability, limiting commercial adoption.

3.3 *ProSeed's On-Site Drying Solution*

ProSeed offers an innovative on-site solution for upcycling brewer's spent grain BSG into a high-value raw material known as Barley Flakes through the combination of mechanical technologies and a drying process. This technology, installed directly at breweries, stabilizes BSG immediately after it exits the brewing process, preserving its food-grade quality. The Barley Flakes are then supplied to ingredient manufacturers for further processing, at their existing facilities for production of specialty flours and protein concentrates as examples. The system is housed in a 40-foot shipping container, making it easy to install and ideal for breweries with limited space for food-grade production.

To understand how ProSeed's system transforms BSG into Barley Flakes, we outline the key stages of the process below.

Stage 1: Transition from Batch Production to a Continuous System

Once the mashing process is complete, the BSG is transferred from the brewery's tank to a BSG storage tank, as the brewing process typically operates in batches. ProSeed's system enables the transition to a continuous process for subsequent stages. The size of the storage tank depends on the size of the brewery's batches and the frequency of brewing.

Stage 2: Mechanical Dehydration

After storage, the BSG is processed through ProSeed's mechanical dehydration system, which removes a significant portion of the water. This is achieved through mechanical pressing, reducing the moisture content from around 80% to below 65%. Mechanical dehydration is highly energy-efficient compared to thermal drying, as pressing water out of the material consumes far less energy. This step is crucial for reducing the overall energy consumption of the process, making it both cost-effective and sustainable.

Stage 3: Low-Temperature Drying

The third stage of the process is low-temperature drying, which further reduces the moisture content of BSG to below 15%. A water activity (aw) value below 0.6 must be reached to ensure stability. This step guarantees that BSG is shelf-stable and can be stored without the risk of spoilage for up to 18 months. Compared to high-temperature drying, lower drying temperatures preserve the nutritional integrity of BSG. Drying at temperatures below 100 °C better preserves its nutritional and functional properties, such as protein quality and bioactive compounds, while preventing off-flavors and color changes (Fig. 4).[32]

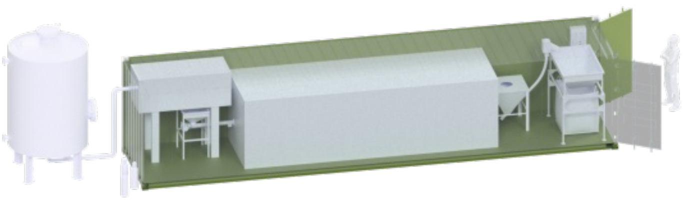

Fig. 4. ProSeed's stabilization and drying unit, is capable of processing up to 4900 tonnes of BSG per year, corresponding to a brewery output of 240,000 hectoliters of beer annually.

3.4 *Barley Flakes: Composition and Versatile Applications*

Following ProSeed's three-stage drying process, BSG is transformed into Barley Flakes (Fig. 5), a food-grade raw material rich in protein and fiber. These flakes are compatible with standard food manufacturing processes, offering ingredient manufacturers a sustainable and economically viable option for food-grade materials.

Fig. 5. Photograph of Barley Flakes, with particle size of d10: 1140 μm; d50: 2340 μm; d97: 4600 μm, where d10 indicates 10% of particles are smaller than 1140 μm, and so on.

Barley Flakes are versatile and used in various applications, including flour production for the bakery sector and as protein concentrates for the meat alternatives market. Their high fiber and protein content, combined with low carbohydrates, make them suitable for producing high-nutrient food ingredients, which complement other grains and legumes ingredients in food recipes. Barley flakes can also serve as substrates for fermentation due to their protein content, rich fiber composition (hemicellulose and cellulose), and diverse nutrients, including vitamins, minerals, amino acids, and phenolic compounds, all of which support microbial growth.[33]

The table below presents the nutritional value of flour made from Barley Flakes, highlighting its high content of fiber, protein, and several essential elements, making it an ideal ingredient for various food applications.

Table 1. Nutritional composition of 100 g of flour produced from Barley Flakes.

NUTRITIONAL VALUES	
Energy (kJ/kcal)	1454/350
Protein (g)	22.4
Fat (g)	9.8
Saturated fat (g)	0.8
Carbohydrates (g)	1.5
Sugars (g)	1.0
Dietary fibre (g)	56.2
Salt (g)	0.03
Calcium (mg)	477
Magnesium (mg)	168
Iron (mg)	13
Manganese (mg)	4.1
Zinc (mg)	7.8
Ash (mg)	3.8
Gluten (mg)	>800

The nutritional composition of flour produced from Barley Flakes underscores its potential for specialized dietary applications, particularly due to its high fiber and protein content, along with its low carbohydrate profile. Despite its richness in essential minerals such as calcium, magnesium, iron, and zinc, further research is necessary to evaluate the bioavailability of these nutrients to fully understand their impact on health and in food formulations.

4. Discussion

The valorization of wet byproducts, such as okara and BSG, offers a significant opportunity to reduce food waste and promote sustainability within the food industry. However, addressing the challenges associated with these wet byproducts is not always straightforward, especially when the primary focus of industries like breweries or tofu manufacturers is producing their core products rather than managing byproduct streams. Since the quality of byproduct management does not directly impact the quality of their main products – beer or tofu – it is not typically a priority unless the solution simplifies their current handling methods and increases revenue. Therefore, handling wet byproducts on-site is often viewed as impractical or outside the scope of their core business model.

In the first case study, the solid-state fermentation of okara yielded a tempeh-like product, providing a promising avenue for converting a high-moisture byproduct into a nutritious food source. We demonstrated that it is possible to directly ferment wet okara at moisture contents of 70 wt%, however, under the conditions of this work, successful fermentation was not possible at the as-produced water content (>80 wt%). That said, it may be possible to further fine-tune fermentation conditions such that mycelium development counterbalances spoilage at >70 wt% humidity, perhaps by using another fungal species, a higher inoculum content, or an additive to the okara (see below).

In the best situation, the okara would be kept fresh, hydrated, and sterile, with little or no drying or other preservation, moving directly from one food production to another. However, implementing a tempeh-like production process at scale requires not only defining the timing and conditions for processing okara, but also assessing whether it is feasible to process it immediately or if an intermediate stabilization or formulation step is necessary. Whether upscaling is warranted or not depends on whether the fermented product has a market that would justify the infrastructure required to couple fermentation to soymilk and tofu production. Considering the mealy texture of our cakes, this goal might perhaps only be achievable by combining the wet okara with another food or food byproduct prior to fermentation to improve the texture and bite of the fermented product. At the same time such an addition might also serve the purpose of lowering the total water content and creating an environment more conducive to air circulation. Indeed, improving the food formulation to not only improve processing but, perhaps even more importantly, palatability, seems essential to make this product stand out among the many plant-based protein alternatives currently available to consumers.

For scenarios where the immediate utilization or transformation of these byproducts is not feasible, stabilizing them becomes essential to prevent microbiological spoilage and contamination. As shown in the second case study, drying, in particular, offers a reliable solution to extend the shelf life of wet byproducts, ensuring they can be processed at a later stage without significant degradation. ProSeed's on-site drying solution for BSG tackles the challenge of rapid spoilage and food-grade preservation. The low-temperature drying method effectively stabilizes BSG, enabling its conversion into Barley Flakes, a high-protein, high-fiber ingredient suitable for a variety of food applications. This method preserves the nutritional integrity of BSG while offering a scalable solution that reduces transportation and energy costs typically associated with handling wet byproducts.

In the case of ProSeed, the first container drying solution is already operational at an industrial scale. The next challenge lies in replicating the process to meet the needs of more breweries and food processors. Additionally, the technology has the potential to be adapted for use with a wide range of other wet byproducts, potentially expanding its impact across different sectors of the food and beverage industry.

5. Conclusion

The findings presented in these case studies align with the principles of a circular economy, demonstrating how food waste can be converted into resources that re-enter the food supply chain. By addressing food waste, we can contribute to reducing the environmental footprint of food production, potentially mitigating some of the impacts on planetary boundaries.

However, challenges remain, particularly in ensuring consistent product quality at scale and optimizing the efficiency and feasibility of both fermentation and drying processes. Furthermore, the development of new products from upcycled byproducts requires careful consideration of industry and consumer acceptance, which may be affected by entrenched preferences for familiar products, as well as taste and price expectations. Future efforts should be directed toward upscaling as well as exploring additional byproducts, microbial strains, or fermentation conditions that can increase the value and diversity of food products derived from wet byproducts. Additionally, collaborations with the food industry and policymakers will be critical in bringing these innovations to market and fostering wider adoption of upcycling practices.

These case studies demonstrate that while some degree of drying is often required to stabilize wet byproducts, technological options available to effectively manage these streams exist. Companies must carefully consider their resources, infrastructure, and long-term goals when deciding how to handle byproducts. Whether through fermentation, drying, using wet forms, or a combination of different treatments, the upcycling of wet byproducts may provide a better path than the status quo of feed or biofuel. Here, future efforts might focus on optimizing these processes to integrate them better into industrial workflows, scaling them up, ensuring they are economically viable, and confirming that there is a market for the products produced. By doing so, food and beverage companies can play a crucial role in advancing sustainability while potentially creating new revenue streams from foods that would otherwise go to waste.

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